Principles of AI Planning

7. State-space search: relaxed planning tasks

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A simple heuristic for deterministic planning

STRIPS (Fikes & Nilsson, 1971) used the number of state variables that differ in current state s and a STRIPS goal $l_1 \wedge \dots \wedge l_n$:

$$h(s) := |\{i \in \{1, \dots, n\} \mid s(a) \not\models l_i\}|.$$

Intuition: more true goal literals ⇝ closer to the goal

⇝ STRIPS heuristic (properties?)

Note: From now on, for convenience we usually write heuristics as functions of states (as above), not nodes.
Node heuristic h' is defined from state heuristic h as $h'(\sigma) := h(state(\sigma))$.

Criticism of the STRIPS heuristic

What is wrong with the STRIPS heuristic?

- quite uninformative:
  the range of heuristic values in a given task is small;
  typically, most successors have the same estimate
- very sensitive to reformulation:
  can easily transform any planning task into an equivalent one where $h(s) = 1$ for all non-goal states (how?)
- ignores almost all problem structure:
  heuristic value does not depend on the set of operators!

⇝ need a better, principled way of coming up with heuristics

Coming up with heuristics in a principled way

General procedure for obtaining a heuristic

Solve an easier version of the problem.

Two common methods:

- relaxation: consider less constrained version of the problem
- abstraction: consider smaller version of real problem

Both have been very successfully applied in planning.
We consider both in this course, beginning with relaxation.

Relaxing a problem

How do we relax a problem?

Example (Route planning for a road network)

The road network is formalized as a weighted graph over points in the Euclidean plane. The weight of an edge is the road distance between two locations.

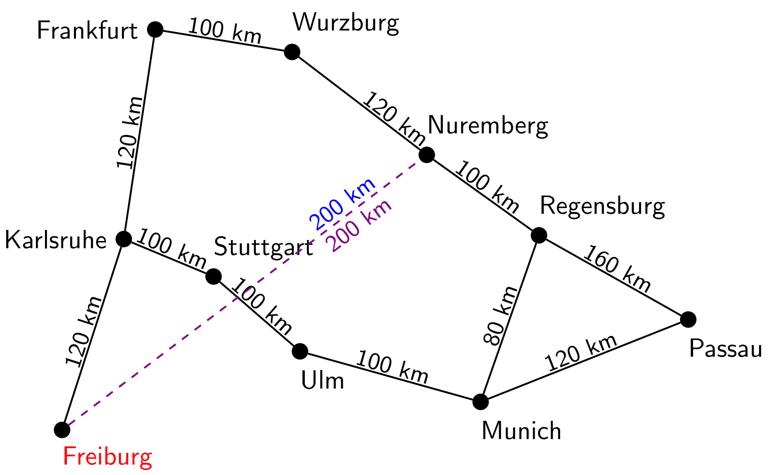
A relaxation drops constraints of the original problem.

Example (Relaxation for route planning)

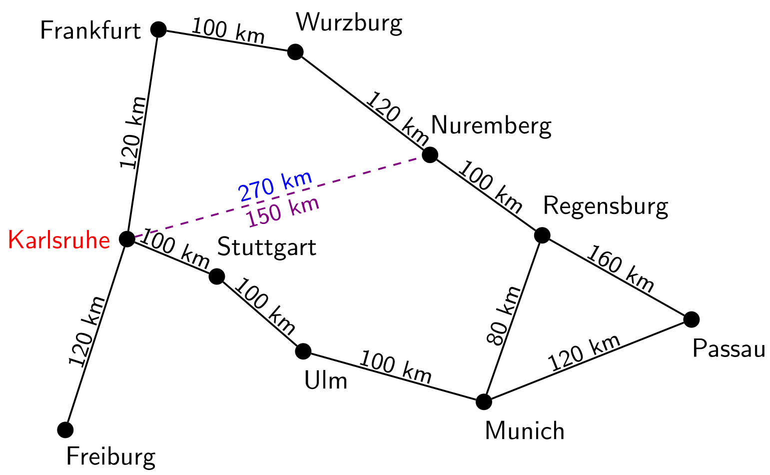
Use the Euclidean distance $\sqrt{|x_1 - y_1|^2 + |x_2 - y_2|^2}$ as a heuristic for the road distance between (x_1, x_2) and (y_1, y_2)
This is a lower bound on the road distance ($\rightsquigarrow$ admissible).

$\rightsquigarrow$ We drop the constraint of having to travel on roads.

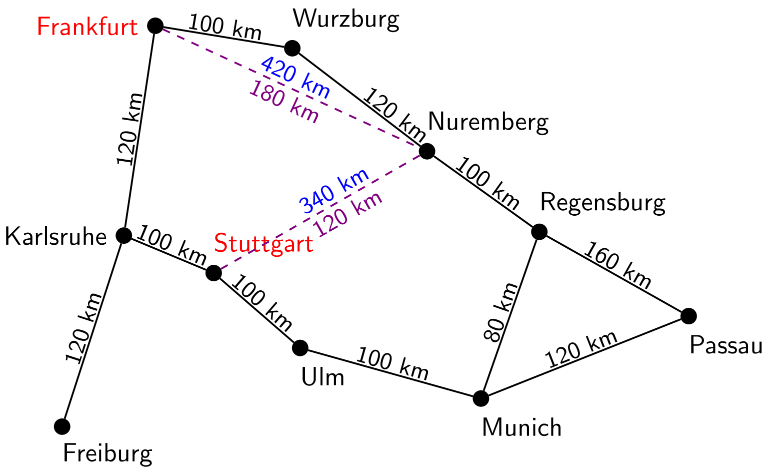
A* using the Euclidean distance heuristic



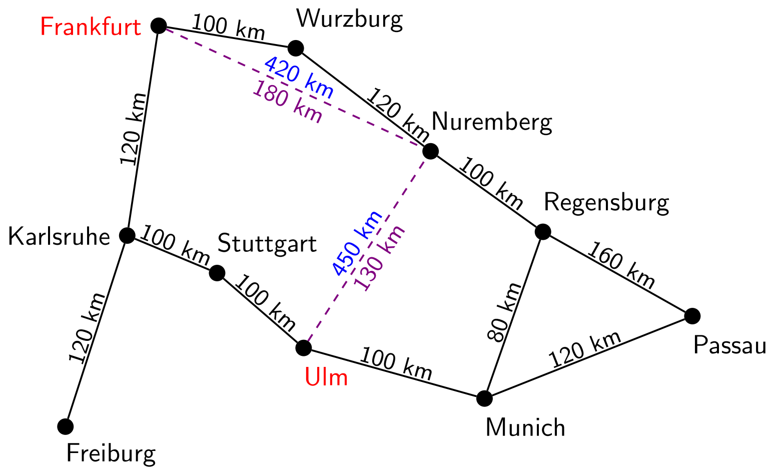
A* using the Euclidean distance heuristic



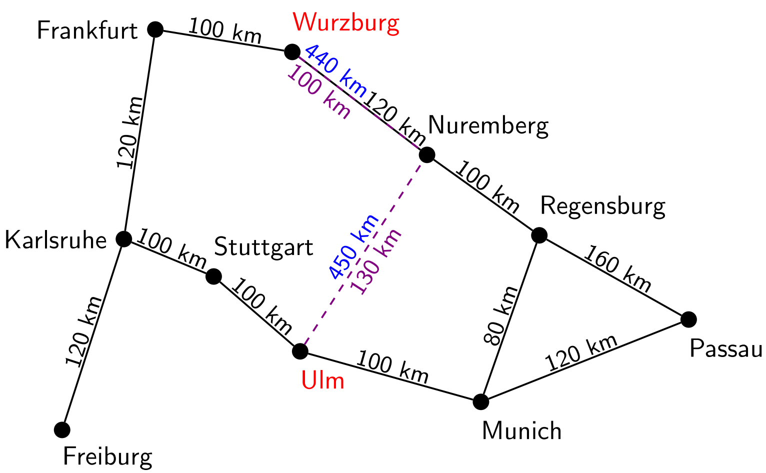
A* using the Euclidean distance heuristic



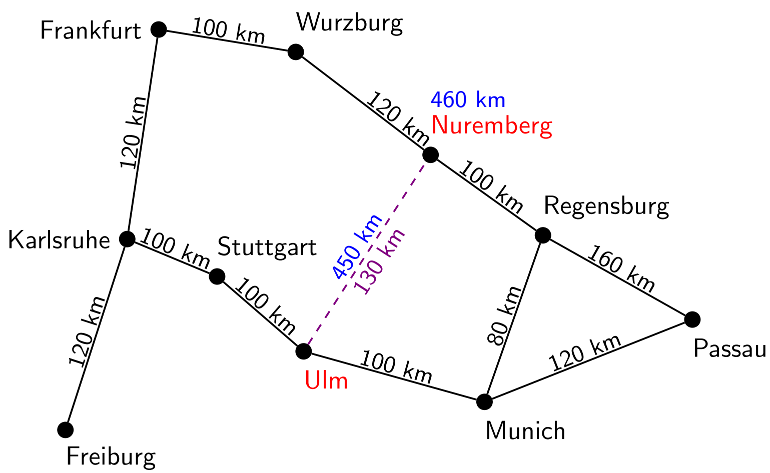
A* using the Euclidean distance heuristic



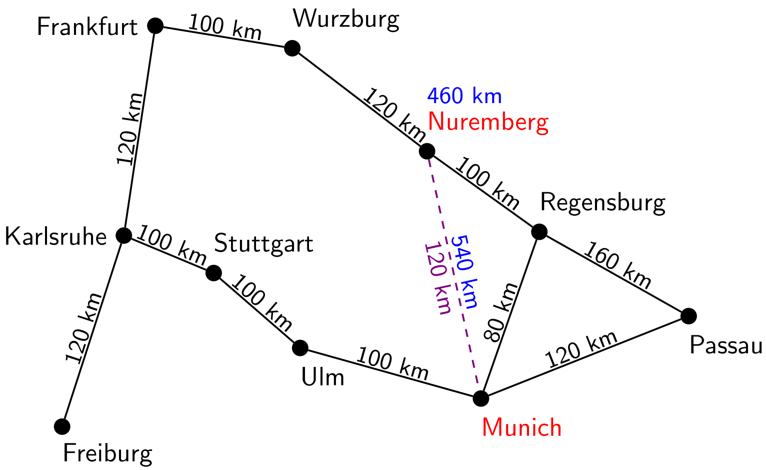
A* using the Euclidean distance heuristic



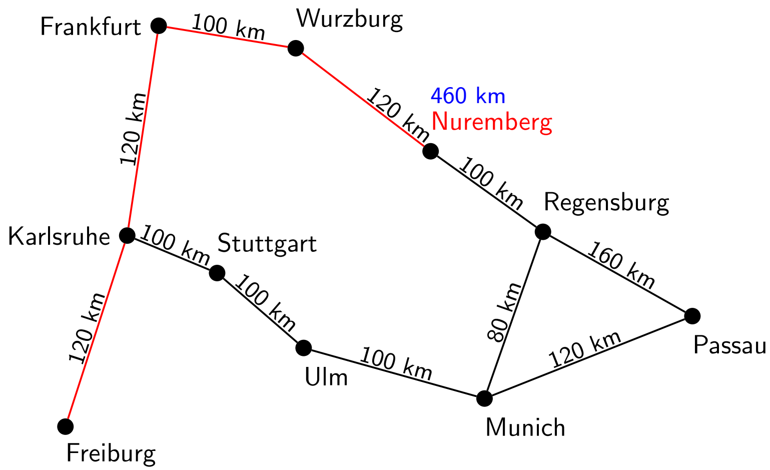
A* using the Euclidean distance heuristic



A* using the Euclidean distance heuristic



A* using the Euclidean distance heuristic



Relaxations for planning

- Relaxation is a general technique for heuristic design:
  - Straight-line heuristic (route planning): Ignore the fact that one must stay on roads.
  - Manhattan heuristic (15-puzzle): Ignore the fact that one cannot move through occupied tiles.
- We want to apply the idea of relaxations to planning.
- Informally, we want to ignore bad side effects of applying operators.

Example (FreeCell)

If we move a card c to a free tableau position, the good effect is that the card formerly below c is now available.
The bad effect is that we lose one free tableau position.

What is a good or bad effect?

Question: Which operator effects are good, and which are bad?

Difficult to answer in general, because it depends on context:

- Locking the entrance door is good if we want to keep burglars out.
- Locking the entrance door is bad if we want to enter.

We will now consider a reformulation of planning tasks that makes the distinction between good and bad effects obvious.

Positive normal form

Definition (operators in positive normal form)

An operator $o = \langle c, e\rangle$ is in positive normal form if it is in normal form, no negation symbols appear in c, and no negation symbols appear in any effect condition in e.

Definition (planning tasks in positive normal form)

A planning task $\langle A, I, O, G\rangle$ is in positive normal form if all operators in O are in positive normal form and no negation symbols occur in the goal G.

Positive normal form: existence

Theorem (positive normal form)

Every planning task Π has an equivalent planning task Π' in positive normal form.
Moreover, Π' can be computed from Π in polynomial time.

Note: Equivalence here means that the represented transition systems of Π and Π', limited to the states that can be reached from the initial state, are isomorphic.

We prove the theorem by describing a suitable algorithm.
(However, we do not prove its correctness or complexity.)

Positive normal form: algorithm

Transformation of $\langle A, I, O, G\rangle$ to positive normal form

Convert all operators $o \in O$ to normal form.
Convert all conditions to negation normal form (NNF).
while any condition contains a negative literal $\neg a$:
    Let a be a variable which occurs negatively in a condition.
    $A := A \cup \{\hat{a}\}$ for some new state variable $\hat{a}$
    $I(\hat{a}) := 1 - I(a)$
    Replace the effect a by $(a \wedge \neg\hat{a})$ in all operators $o \in O$.
    Replace the effect $\neg a$ by $(\neg a \wedge \hat{a})$ in all operators $o \in O$.
    Replace $\neg a$ by $\hat{a}$ in all conditions.
Convert all operators $o \in O$ to normal form (again).

Here, *all conditions* refers to all operator preconditions, operator effect conditions and the goal.

Positive normal form: example

Example (transformation to positive normal form)

$$
\begin{aligned}
A &= \{\mathit{home}, \mathit{uni}, \mathit{lecture}, \mathit{bike}, \mathit{bike\text{-}locked}\}\\
I &= \{\mathit{home} \mapsto 1, \mathit{bike} \mapsto 1, \mathit{bike\text{-}locked} \mapsto 1,\\
&\quad\ \mathit{uni} \mapsto 0, \mathit{lecture} \mapsto 0\}\\
O &= \{\langle \mathit{home} \wedge \mathit{bike} \wedge \neg \mathit{bike\text{-}locked}, \neg \mathit{home} \wedge \mathit{uni}\rangle,\\
&\quad\ \langle \mathit{bike} \wedge \mathit{bike\text{-}locked}, \neg \mathit{bike\text{-}locked}\rangle,\\
&\quad\ \langle \mathit{bike} \wedge \neg \mathit{bike\text{-}locked}, \mathit{bike\text{-}locked}\rangle,\\
&\quad\ \langle \mathit{uni}, \mathit{lecture} \wedge ((\mathit{bike} \wedge \neg \mathit{bike\text{-}locked}) \rhd \neg \mathit{bike})\rangle\}\\
G &= \mathit{lecture} \wedge \mathit{bike}
\end{aligned}
$$

Positive normal form: example

Example (transformation to positive normal form)

$$
\begin{aligned}
A &= \{home, uni, lecture, bike, bike\text{-}locked\}\\
I &= \{home \mapsto 1, bike \mapsto 1, bike\text{-}locked \mapsto 1,\\
&\quad uni \mapsto 0, lecture \mapsto 0\}\\
O &= \{\langle home \land bike \land \neg bike\text{-}locked, \neg home \land uni\rangle,\\
&\quad \langle bike \land bike\text{-}locked, \neg bike\text{-}locked\rangle,\\
&\quad \langle bike \land \neg bike\text{-}locked, bike\text{-}locked\rangle,\\
&\quad \langle uni, lecture \land ((bike \land \neg bike\text{-}locked) \rhd \neg bike)\rangle\}\\
G &= lecture \land bike
\end{aligned}
$$

Identify state variable a occurring negatively in conditions.

Positive normal form: example

Example (transformation to positive normal form)

$$
\begin{aligned}
A &= \{home, uni, lecture, bike, bike\text{-}locked, bike\text{-}unlocked\}\\
I &= \{home \mapsto 1, bike \mapsto 1, bike\text{-}locked \mapsto 1,\\
&\quad uni \mapsto 0, lecture \mapsto 0, bike\text{-}unlocked \mapsto 0\}\\
O &= \{\langle home \land bike \land \neg bike\text{-}locked, \neg home \land uni\rangle,\\
&\quad \langle bike \land bike\text{-}locked, \neg bike\text{-}locked\rangle,\\
&\quad \langle bike \land \neg bike\text{-}locked, bike\text{-}locked\rangle,\\
&\quad \langle uni, lecture \land ((bike \land \neg bike\text{-}locked) \rhd \neg bike)\rangle\}\\
G &= lecture \land bike
\end{aligned}
$$

Introduce new variable $\hat{a}$ with complementary initial value.

Positive normal form: example

Example (transformation to positive normal form)

$$
\begin{aligned}
A &= \{home, uni, lecture, bike, bike\text{-}locked, bike\text{-}unlocked\}\\
I &= \{home \mapsto 1, bike \mapsto 1, bike\text{-}locked \mapsto 1,\\
&\quad uni \mapsto 0, lecture \mapsto 0, bike\text{-}unlocked \mapsto 0\}\\
O &= \{\langle home \land bike \land \neg bike\text{-}locked, \neg home \land uni\rangle,\\
&\quad \langle bike \land bike\text{-}locked, \neg bike\text{-}locked\rangle,\\
&\quad \langle bike \land \neg bike\text{-}locked, bike\text{-}locked\rangle,\\
&\quad \langle uni, lecture \land ((bike \land \neg bike\text{-}locked) \rhd \neg bike)\rangle\}\\
G &= lecture \land bike
\end{aligned}
$$

Identify effects on variable a.

Positive normal form: example

Example (transformation to positive normal form)

$$
\begin{aligned}
A &= \{home, uni, lecture, bike, bike\text{-}locked, bike\text{-}unlocked\}\\
I &= \{home \mapsto 1, bike \mapsto 1, bike\text{-}locked \mapsto 1,\\
&\quad uni \mapsto 0, lecture \mapsto 0, bike\text{-}unlocked \mapsto 0\}\\
O &= \{\langle home \land bike \land \neg bike\text{-}locked, \neg home \land uni\rangle,\\
&\quad \langle bike \land bike\text{-}locked, \neg bike\text{-}locked \land bike\text{-}unlocked\rangle,\\
&\quad \langle bike \land \neg bike\text{-}locked, bike\text{-}locked \land \neg bike\text{-}unlocked\rangle,\\
&\quad \langle uni, lecture \land ((bike \land \neg bike\text{-}locked) \rhd \neg bike)\rangle\}\\
G &= lecture \land bike
\end{aligned}
$$

Introduce complementary effects for $\hat{a}$.

Positive normal form: example

Example (transformation to positive normal form)

$$A = \{home, uni, lecture, bike, bike\text{-}locked, bike\text{-}unlocked\}$$
$$I = \{home \mapsto 1, bike \mapsto 1, bike\text{-}locked \mapsto 1, uni \mapsto 0, lecture \mapsto 0, bike\text{-}unlocked \mapsto 0\}$$
$$O = \{\langle home \land bike \land \neg bike\text{-}locked, \neg home \land uni\rangle, \langle bike \land bike\text{-}locked, \neg bike\text{-}locked \land bike\text{-}unlocked\rangle, \langle bike \land \neg bike\text{-}locked, bike\text{-}locked \land \neg bike\text{-}unlocked\rangle, \langle uni, lecture \land ((bike \land \neg bike\text{-}locked) \rhd \neg bike)\rangle\}$$
$$G = lecture \land bike$$

Identify negative conditions for a.

Positive normal form: example

Example (transformation to positive normal form)

$$A = \{home, uni, lecture, bike, bike\text{-}locked, bike\text{-}unlocked\}$$
$$I = \{home \mapsto 1, bike \mapsto 1, bike\text{-}locked \mapsto 1, uni \mapsto 0, lecture \mapsto 0, bike\text{-}unlocked \mapsto 0\}$$
$$O = \{\langle home \land bike \land bike\text{-}unlocked, \neg home \land uni\rangle, \langle bike \land bike\text{-}locked, \neg bike\text{-}locked \land bike\text{-}unlocked\rangle, \langle bike \land bike\text{-}unlocked, bike\text{-}locked \land \neg bike\text{-}unlocked\rangle, \langle uni, lecture \land ((bike \land bike\text{-}unlocked) \rhd \neg bike)\rangle\}$$
$$G = lecture \land bike$$

Replace by positive condition $\hat{a}$.

Positive normal form: example

Example (transformation to positive normal form)

$$A = \{home, uni, lecture, bike, bike\text{-}locked, bike\text{-}unlocked\}$$
$$I = \{home \mapsto 1, bike \mapsto 1, bike\text{-}locked \mapsto 1, uni \mapsto 0, lecture \mapsto 0, bike\text{-}unlocked \mapsto 0\}$$
$$O = \{\langle home \land bike \land bike\text{-}unlocked, \neg home \land uni\rangle, \langle bike \land bike\text{-}locked, \neg bike\text{-}locked \land bike\text{-}unlocked\rangle, \langle bike \land bike\text{-}unlocked, bike\text{-}locked \land \neg bike\text{-}unlocked\rangle, \langle uni, lecture \land ((bike \land bike\text{-}unlocked) \rhd \neg bike)\rangle\}$$
$$G = lecture \land bike$$

Relaxed planning tasks: idea

In positive normal form, good and bad effects are easy to distinguish:

- Effects that make state variables true are good (add effects).
- Effects that make state variables false are bad (delete effects).

Idea for the heuristic: Ignore all delete effects.

Relaxed planning tasks

Definition (relaxation of operators)

The relaxation o^+ of an operator $o = \langle c, e \rangle$ in positive normal form is the operator which is obtained by replacing all negative effects $\neg a$ within e by the do-nothing effect $\top$.

Definition (relaxation of planning tasks)

The relaxation Π^+ of a planning task $\Pi = \langle A, I, O, G \rangle$ in positive normal form is the planning task $\Pi^+ := \langle A, I, \{o^+ \mid o \in O\}, G \rangle$.

Definition (relaxation of operator sequences)

The relaxation of an operator sequence $\pi = o_1 \dots o_n$ is the operator sequence $\pi^+ := {o_1}^+ \dots {o_n}^+$.

Relaxed planning tasks: terminology

- Planning tasks in positive normal form without delete effects are called relaxed planning tasks.
- Plans for relaxed planning tasks are called relaxed plans.
- If Π is a planning task in positive normal form and π^+ is a plan for Π^+, then π^+ is called a relaxed plan for Π.

Dominating states

The on-set $on(s)$ of a state s is the set of true state variables in s, i.e. $on(s) = s^{-1}(\{1\})$.
A state s' dominates another state s iff $on(s) \subseteq on(s')$.

Lemma (domination)

Let s and s' be valuations of a set of propositional variables and let χ be a propositional formula which does not contain negation symbols.
If $s \models \chi$ and s' dominates s, then $s' \models \chi$.

Proof by induction over the structure of χ.

The relaxation lemma

For the rest of this chapter, we assume that all planning tasks are in positive normal form.

Lemma (relaxation)

Let s be a state, let s' be a state that dominates s,
and let π be an operator sequence which is applicable in s.
Then π^+ is applicable in s' and $app_{\pi^+}(s')$ dominates $app_\pi(s)$.
Moreover, if π leads to a goal state from s, then π^+ leads to a goal state from s'.

Proof.

The "moreover" part follows from the rest by the domination lemma.
Prove the rest by induction over the length of π.

Base case: $\pi = \epsilon$

$app_{\pi^+}(s') = s'$ dominates $app_\pi(s) = s$ by assumption.

The relaxation lemma (ctd.)

Proof (ctd.)

Inductive case: $\pi = o_1 \dots o_{n+1}$
By the induction hypothesis, $o_1{}^+ \dots o_n{}^+$ is applicable in s', and $t' = app_{o_1{}^+ \dots o_n{}^+}(s')$ dominates $t = app_{o_1 \dots o_n}(s)$.

Let $o := o_{n+1} = \langle c, e \rangle$ and $o^+ = \langle c, e^+ \rangle$. By assumption, o is applicable in t, and thus $t \models c$. By the domination lemma, we get $t' \models c$ and hence o^+ is applicable in t'. Therefore, π^+ is applicable in s'.

Because o is in positive normal form, all effect conditions satisfied by t are also satisfied by t' (by the domination lemma). Therefore, $([e]_t \cap A) \subseteq [e^+]_{t'}$ (where A is the set of state variables, or positive literals).

We get
$on(app_\pi(s)) \subseteq on(t) \cup ([e]_t \cap A) \subseteq on(t') \cup [e^+]_{t'} = on(app_{\pi^+}(s'))$, and thus $app_{\pi^+}(s')$ dominates $app_\pi(s)$. □

Consequences of the relaxation lemma

Corollary (relaxation leads to dominance and preserves plans)

Let π be an operator sequence which is applicable in state s.
Then π^+ is applicable in s and $app_{\pi^+}(s)$ dominates $app_\pi(s)$.
If π is a plan for Π, then π^+ is a plan for Π^+.

Proof.

Apply relaxation lemma with $s' = s$. □

- ⇝ Relaxations of plans are relaxed plans.
- ⇝ Relaxations are no harder to solve than the original task.
- ⇝ Optimal relaxed plans are never longer than optimal plans for original tasks.

Consequences of the relaxation lemma (ctd.)

Corollary (relaxation preserves dominance)

Let s be a state, let s' be a state that dominates s,
and let π^+ be a relaxed operator sequence applicable in s.
Then π^+ is applicable in s' and $app_{\pi^+}(s')$ dominates $app_{\pi^+}(s)$.

Proof.

Apply relaxation lemma with π^+ for π, noting that $(\pi^+)^+ = \pi^+$. □

- ⇝ If there is a relaxed plan starting from state s, the same plan can be used starting from a dominating state s'.
- ⇝ Making a transition to a dominating state never hurts in relaxed planning tasks.

Monotonicity of relaxed planning tasks

We need one final property before we can provide an algorithm for solving relaxed planning tasks.

Lemma (monotonicity)

Let $o^+ = \langle c, e^+ \rangle$ be a relaxed operator and let s be a state in which o^+ is applicable.
Then $app_{o^+}(s)$ dominates s.

Proof.

Since relaxed operators only have positive effects, we have $on(s) \subseteq on(s) \cup [e^+]_s = on(app_{o^+}(s))$. □

- ⇝ Together with our previous results, this means that making a transition in a relaxed planning task never hurts.

Greedy algorithm for relaxed planning tasks

The relaxation and monotonicity lemmas suggest the following algorithm for solving relaxed planning tasks:

Greedy planning algorithm for $\langle A, I, O^+, G \rangle$

$s := I$
$\pi^+ := \epsilon$
forever:
  if $s \models G$:
    return π^+
  else if there is an operator $o^+ \in O^+$ applicable in s with $app_{o^+}(s) \neq s$:
    Append such an operator o^+ to π^+.
    $s := app_{o^+}(s)$
  else:
    return unsolvable

Correctness of the greedy algorithm

The algorithm is sound:

- If it returns a plan, this is indeed a correct solution.
- If it returns "unsolvable", the task is indeed unsolvable
  - Upon termination, there clearly is no relaxed plan from s.
  - By iterated application of the monotonicity lemma, s dominates I.
  - By the relaxation lemma, there is no solution from I.

What about completeness (termination) and runtime?

- Each iteration of the loop adds at least one atom to $on(s)$.
- This guarantees termination after at most $|A|$ iterations.
- Thus, the algorithm can clearly be implemented to run in polynomial time.
  - A good implementation runs in $O(\|\Pi\|)$.

Using the greedy algorithm as a heuristic

We can apply the greedy algorithm within heuristic search:

- In a search node σ, solve the relaxation of the planning task with $state(\sigma)$ as the initial state.
- Set $h(\sigma)$ to the length of the generated relaxed plan.

Is this an admissible heuristic?

- Yes if the relaxed plans are optimal (due to the plan preservation corollary).
- However, usually they are not, because our greedy planning algorithm is very poor.

(What about safety? Goal-awareness? Consistency?)

The set cover problem

To obtain an admissible heuristic, we need to generate optimal relaxed plans. Can we do this efficiently?

This question is related to the following problem:

Problem (set cover)

Given: *a finite set U, a collection of subsets $C = \{C_1, \dots, C_n\}$ with $C_i \subseteq U$ for all $i \in \{1, \dots, n\}$, and a natural number K.*

Question: *Does there exist a set cover of size at most K, i.e., a subcollection $S = \{S_1, \dots, S_m\} \subseteq C$ with $S_1 \cup \dots \cup S_m = U$ and $m \leq K$?*

The following is a classical result from complexity theory:

Theorem

The set cover problem is NP-complete.

Hardness of optimal relaxed planning

Theorem (optimal relaxed planning is hard)

The problem of deciding whether a given relaxed planning task has a plan of length at most K is NP-complete.

Proof.

For membership in NP, guess a plan and verify. It is sufficient to check plans of length at most $|A|$, so this can be done in nondeterministic polynomial time.

For hardness, we reduce from the set cover problem.

Hardness of optimal relaxed planning (ctd.)

Proof (ctd.)

Given a set cover instance $\langle U, C, K\rangle$, we generate the following relaxed planning task $\Pi^+ = \langle A, I, O^+, G\rangle$:

- $A = U$
- $I = \{a \mapsto 0 \mid a \in A\}$
- $O^+ = \{\langle \top, \bigwedge_{a \in C_i} a\rangle \mid C_i \in C\}$
- $G = \bigwedge_{a \in U} a$

If S is a set cover, the corresponding operators form a plan. Conversely, each plan induces a set cover by taking the subsets corresponding to the operators. Clearly, there exists a plan of length at most K iff there exists a set cover of size K.

Moreover, Π^+ can be generated from the set cover instance in polynomial time, so this is a polynomial reduction. □

Using relaxations in practice

How can we use relaxations for heuristic planning in practice?

Different possibilities:

- Implement an optimal planner for relaxed planning tasks and use its solution lengths as an estimate, even though it is NP-hard.
  $\rightsquigarrow$ h^+ heuristic
- Do not actually solve the relaxed planning task, but compute an estimate of its difficulty in a different way.
  $\rightsquigarrow$ h_{max} heuristic, h_{add} heuristic
- Compute a solution for relaxed planning tasks which is not necessarily optimal, but "reasonable".
  $\rightsquigarrow$ h_{FF} heuristic